

Laboratory gamma-ray pulsar

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The mechanism by which gamma-ray pulsars shine might be reproducible in a laboratory. This claim is supported by three observations: (i) properly focusing a few PW optical laser gives an electromagnetic field in the so-called Aristotelian regime, when a test electron is radiation-overdamped; (ii) the Goldreich-Julian number density of this electromagnetic field (the number density of elementary charges needed for a nearly full conversion of optical power into gamma-rays) is of order the electron number density in a solid; (iii) above about 50PW, the external source of electrons is not needed – charges will be created by a pair production avalanche.

I. INTRODUCTION

It appears that a gamma-ray pulsar can be created in a laboratory. Real pulsars are efficiently converting the large-scale Poynting flux into gamma-rays (up to order-unity efficiency for a weak axisymmetric pulsar, [1] and references therein). The laboratory pulsar is expected to efficiently convert optical light into gamma-rays.

At the level of estimates, the conditions needed for an efficient Poynting-to-gamma conversion appear to be reproducible in a laboratory. All one needs is (i) Aristotle number above one, meaning radiation damping stronger than inertia, and (ii) the right (namely Goldreich-Julian, [2]) number density of electrons. We discuss these two conditions in turn.

II. ARISTOTELIAN REGIME

Consider a test electron in the electromagnetic field of generic geometry, $|E^2 - B^2| \sim |\mathbf{E} \cdot \mathbf{B}| \sim F^2 > 0$, with characteristic length scale λ , and characteristic time scale λ/c . Let us estimate the characteristic Lorentz factor of the electron, γ . On the one hand, there exists a maximal possible γ associated to the full “potential drop” of the field:

$$\gamma_{\max} \sim \frac{eF\lambda}{mc^2}, \quad (1)$$

where $F \sim E \sim B$ is the characteristic value of electric and magnetic fields, e is the electron charge, m is the electron mass. On the other hand, there exists a terminal Lorentz factor at which the radiation damping balances the Lorentz force:

$$\gamma_{\text{term}} \sim \left(\frac{F\lambda^2}{e} \right)^{1/4}. \quad (2)$$

The electron is radiation-overdamped (the field is in the Aristotelian regime) if the terminal Lorentz factor is reached in less than the characteristic length scale, that is if

$$\gamma_{\max} \gtrsim \gamma_{\text{term}}. \quad (3)$$

Estimating the field from

$$L \sim c\lambda^2 F^2, \quad (4)$$

where L , erg/s, is the laser power, we write the condition of radiation overdamping as

$$\text{Ar} \equiv \frac{L}{L_e} \left(\frac{\lambda}{r_e} \right)^{-2/3} \gtrsim 1, \quad (5)$$

where we have defined the dimensionless Aristotle number Ar , with $L_e \equiv \frac{mc^3}{r_e} = 8.7 \times 10^{16} \text{erg/s}$ – the classical electron luminosity, and $r_e \equiv \frac{e^2}{mc^2} = 2.8 \times 10^{-13} \text{cm}$ – the classical electron radius.

Assuming that a (split) laser pulse of power $L_{\text{PW}} \times 10^{22} \text{erg/s}$ is focused onto a region of size $\lambda_\mu \times 10^{-4} \text{cm}$, we get an Aristotle number

$$\text{Ar} \sim 0.2 L_{\text{PW}} \lambda_\mu^{-2/3}. \quad (6)$$

For $\lambda_\mu = 0.5$ and $L_{\text{PW}} > 3$, we have $\text{Ar} > 1$.

In Aristotelian regime, $\text{Ar} \gtrsim 1$, the work done by the field goes into emission of curvature photons rather than into accelerating electrons. The characteristic photon energy is

$$\epsilon \sim \frac{mc^2}{\alpha} \text{Ar}^{3/8}, \quad (7)$$

where α is the fine structure constant. Pulsars have $\text{Ar} \gg 1$ and emit above about 1GeV. “Aristotelian lasers” should emit above about 100MeV.

III. GOLDREICH-JULIAN NUMBER DENSITY

Each electron emits gamma-rays at a power $\sim eFc$; if we want to convert the entire laser pulse into gamma-rays, the number density of electrons n should be

$$n \sim \frac{L}{\lambda^3 eFc} \sim \frac{c\lambda^2 F^2}{\lambda^3 eFc} \sim \frac{F}{e\lambda}. \quad (8)$$

In pulsar physics, the last expression is known as the Goldreich-Julian density – this is the number density of elementary charges needed to noticeably alter the external field $\sim F$. Numerically,

$$n_{\text{GJ}} \sim 1.2 \times 10^{23} L_{\text{PW}}^{1/2} \lambda_\mu^{-2} \text{cm}^{-3} \quad (9)$$

is of order the number density in a solid.

We also note that above about 50PW, the pair avalanche will (over) produce the necessary charge density starting from a single seed charge as described in [3]: a seed charge emits gamma rays; gamma-rays pair produce in external magnetic field; pairs then emit gamma-rays, etc.

conversion should occur, enabled by the same mechanism by which the gamma-ray pulsars shine.

IV. CONCLUSION

When powerful lasers are properly focused on a target or even on vacuum, an efficient optical to gamma-ray

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- [1] A. Gruzinov, arXiv:1402.1520 (2014) (1975)
 - [2] P. Goldreich, W. H. Julian, *Astrophys. J.* **157**, 869 (1969)
 - [3] M. A. Ruderman, P. G. Sutherland, *Astrophys. J.* **196**, 51